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Debris flows in southeast Brazil: susceptibility assessment for watersheds and vulnerability assessment of buildings

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Abstract

Debris flows is one of the primary mass movement processes in the Serra do Mar, a system of escarpments and mountains that stretches more than 1,500 km in south and southeast of Brazil. Usually, these processes cause environmental and social damages. On March 1967 only one small city was affected by 947 mm, with 115 mm on the 17th and 420 mm on the 18th and triggered numerous landslides and debris flows with the great mobilization of material, reaching a 15 km radius, causing approximately 440 fatalities. Approximately 50 years later, another city, located in the same mountain range, was affected by cumulative rainfall of 150 mm/6 hours causing deaths and houses destroyed and structural damage to bridges. Thus, the objective of this work was to evaluate of vulnerability to debris flows in some watersheds located in two cities of the Serra do Mar affected in 1967 and 2014, respectively. For this purpose, some procedures were defined: (a) the evaluation of the vulnerability of buildings, considered, for instance, the number of floors, the presence of broad terraces, large doors, windows and high walls surrounding the buildings. (b) elaboration of indicators and maps of vulnerability that consider the hazard properties, the exposure, preparedness and prevention of elements at risk; (c) elaboration of indicators and map of risk perception. The results show38 areas with vulnerable construction to debris flows: 8%-high;70%-medium;22%-low vulnerability of buildings. As preliminary results, an inventory of damages was provided from the sectors of the affected districts and preliminary mapping of the debris flow.

Keywords: Serra do Mar, Brazil, Morphometric Parameters, PTVA, Vulnerability

1. Introduction

Debris flows is one of the primary mass movement processes in the Serra do Mar, associated with the rainy season between December and March when 60% of the annual average precipitation of 3,300 mm occurs. The Serra do Mar is a mountain range that extends for about 1,500 km along the south and southeast coast of Brazil. The region has great economic importance since it is crossed by the major land transportation network that connects the city of São Paulo to other large metropolitan areas, as well as to the port of Santos. According to Almeida (1953), the Serra do Mar is one of the most relevant orographic features in the Atlantic coast of the South American continent, and it is known for having the most "Tormented" relief in Brazil due to its steep slopes, tectonic processes, and faults. It is an outstanding feature in the Brazilian terrain for its grand geomorphological features and its role on human occupation from the colonial period to present. Since the 1960s, catastrophic important events were recorded, resulting in millions of dollars in economic loss, thousands of fatalities and homelessness. Several events are remarkable in Brazilian history, particularly in the years 1966, 1967, 1985, 1988, 1995, 2008, 2009, 2010, 2011 and 2014 (Table 1). Thus, the objective of this work was to evaluate the vulnerability of debris flows in some watersheds located in two cities of the

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Serra do Mar, affected in 1967 and 2014, respectively.

Table 1: Occurrences of mass movements (landslides and debris flows) in the Serra do Mar, highlighting the events studied in this paper.

Year	LOCATION (STATE)	Rain	Area (Km²)/Speed (m/s)/Volume (m³)	LOSSES (nº deaths); other damage
1928	Monte Serrate (SP)	649 mm/Jan and 564 mm/Feb.	Vol: > $1x10^5$	(60); destruction of Santa Casa
1958	Monte Serrate (SP)	373 mm/24 h	-	(43); destruction of 100 houses
1966	Rio de Janeiro (RJ)	> 250 mm/<12 h	-	(>230)
1967	Serra das Araras (RJ)	275 mm/24 h	Vol: > $10x10^6$	(1200); > 100 houses destroyed, damage to highways, destruction of the hydroelectric plant
	Caraguatatuba (SP)	580 mm/48 h	Vol: > $7.6x10^6$	(120); 400 houses destroyed, damage to highways
1971	Santos-Jundiaí Railway (SP)	-	Vol: $1x10^5$ (estimated)	Steel viaduct destroyed, works for slope stabilization
1974	Tubarão (SP)	394 mm/ 72 h 742 mm/16 days	-	(195); urban area flooded
1975-1976	Grota Funda (SP)	-	S:8.4/Vol: > $10x10^6$	Pillars of railway bridge damaged
1976	Cachoeira River (SP)	276 mm/24 h	A:4/Vol: $1x10^5$	Flooding for industries, two rock-filled and earth-filled dams was built
1985	Cubatão (SP)	380 mm/48 h	-	(10)
1988	Petrópolis (RJ)	145 mm/24 h	-	(171); 5,000 displaced, 1,100 homes interdicted
	Rio de Janeiro (RJ)	-	-	(~300); destruction of dozens of homes
1994	Cubatão (SP)	60 mm/24 h	A:2.64/S:10 Vol: $3x10^5$	Flooding of Petrobrás Refinery, interruption of operations and clean-up (US$44 mil)
1996	Cubatão (SP)		A: 2.64/S: > 10 Vol.: $1.6x10^4$	Clean-up works
	Oswaldo Cruz Highway (SP)	10 mm/10 min 442 mm/13 h	-	Highway damaged, works for slope stabilization, water capture station affected
	Papagaio River Basin (RJ)	202 mm/24 h	A: 2.13/Vol.: $9x10^4$	(1); hundreds of houses destroyed
	Quitite River Basin (RJ)	202 mm/24 h	A: 2.53 Vol.: $4x10^4$	houses destroyed
	Rio de Janeiro (RJ)	301 mm/72 h		(54)
1999	Anchieta Highway (SP)	128 mm/24 h 274 mm/72 h	Vol.:$3x10^5$	200 m of the affected area, traffic stopped for several weeks, water capture station affected
2001	Rio de Janeiro, Petrópolis (RJ)	300 mm/24 h	-	(40);164 wounded
2002	Petrópolis (RJ)		-	(88)
2008	Santa Catarina (SC)	720 mm/72 h	-	(135); 80,000 displaced/homeless, 85 municipalities in state of emergency
2010	Angra dos Reis (RJ)	143 mm/24 h	-	(53)
	Rio de Janeiro	120 mm/24 h	Vol: 680 m³	(253) 1,410 displaced, 368 homeless
2011	Rio de Janeiro			
	Córrego Dantas (stream) (RJ)	269 mm/72 h	A: 52	(429); 3,220 disappeared, 2,031 homeless, displaced, and many economic losses,
	Córrego Vieira (stream) (RJ)	269 mm/72 h	A: 33	
	Córrego da Posse (stream) (RJ)	92.6 mm/72 h	A: 12	(343); 9,110 disappeared, homeless, 6,727 displaced and numerous losses
	Córrego do Cuiabá (stream) (RJ)	35.8 mm/72 h	A: 36	(71); 6,223 disappeared, homeless, 191 displaced and numerous losses
	Antonina (PR)			(4)
2013	Córrego do Pilões (stream) (SP)	23 mm/10 min 115 mm/1 h 273 mm09 h	-	Damage to the water reservoir, chlorine cylinders, and road service station destroyed
	Petrópolis (RJ)			(31); 4,000 displaced
2014	Itaóca	150 mm/6 hours		Structural damage to bridges, destroyed houses, two disappeared and 25 death

Source: adapted from Vieira e Gramani (2015). A = Area (Km²), S = Speed (m/s) and Vol = Volume (m³)

2. Methods

We selected eight basins in two areas of the Serra do Mar affected by intense rainfall, trigging shallow landslides, debris flows, mudflows, and flash floods. Area 1 (A1) is in the northern portion of the Serra do Mar and Area 2 (A2) south of this escarpment in the State of São Paulo (Fig. 1). In A1 five basins were selected (Massaguaçu, Guaxinduba, Santo Antonio, Ribeirão da Aldeia, and Pau d'alho) with and without records deposits of the debris flows generated in 1967. In this area the mass movements were triggered by intense rainfall events during the summer of 1966/1967 (Fig. 2); rain occurred almost every day that summer and reached 945.6 mm by March 1967. The 535-mm rainfall recorded on the 17th and 18th of that month as responsible for the occurrence of hundreds of shallow landslides and debris flows; these events left their mark on the landscape and can still be seen today in the extensive deep scars on the slopes and large deposits of blocks in the slope ruptures (De Ploey and Cruz 1979).

Approximately 50 years later, on 2014, another city, Itaóca, located in the same orographic feature was affected by cumulative rainfall of 150 mm/6 hours causing deaths with houses destroyed and structural damage to bridges (Fig. 2). In this area we selected three basins more: two basins with records of landslides and debris flows (Palmital 1 and Gurutuba) and a third basin, with similar morphological characteristics, on the other hand, without any record of any landslide or debris flows registered.

It was evaluated the influence of all 8 morphometric parameters to debris flows in the 8 basins, however in only one of them, the Guaxinduba, it was possible to estimate the vulnerability of the constructions to debris flows using the PTVA method.

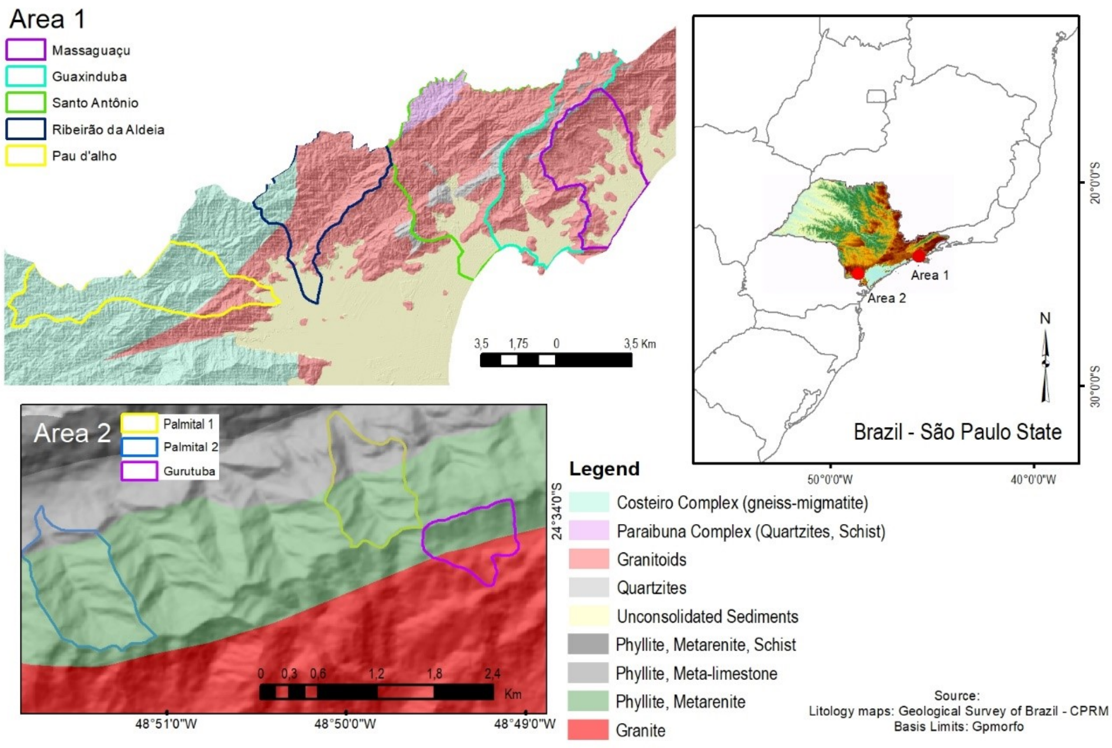

Fig. 1. Location of the eight basins in the Serra do Mar, State of São Paulo.

Fig. 2. (A, B) Mass movements in the Serra do Mar, Caraguatatuba, on March 1967 (C, D) and Itaóca municipality on January 2014. Source: Marcelo Gramani; Municipal Archive Caraguatatuba

2.1 Morphometric parameters

Morphometric parameters have been used by some authors to evaluate the susceptibility of basins to debris flows, because some of these parameters, like drainage channel and slope curvature, sediment availability, shape and area of the basin can influence in the dynamics of the debris flows, including their range, the disposal of the deposits and their magnitude of destruction.

The morphometric parameters used (Drainage Density; Ruggedness Index; Circularity Index; Relief Ratio; Drainage Hierarchy; Slope Mean Channel; Curvature Concave) were defined from literature (Augusto Filho, 1993; De Scally et al., 2001; Jakob, 2005; Chen and Yu, 2011; Dias et al., 2016). The mapping of those parameters derived from two sets of elevation data, one a topographic map (1:10,000 scale) and SRTM (1 arc-sec). The litho structural data were obtained from the geologic map from Brazilian's Geologic Service (Fig. 2).

The debris flows mapping was carried out using the research made by Cruz (1974) as a base, interpretation of aerial photographs in scale 1:25.000 and satellite images, fieldwork, where were collected the characteristics of the deposits. The information was spatialized using the location and characteristics of the deposits, being elaborated a classification of the deposits based in boulders size - “Small, Medium, Large and Very Large,” based on the classification proposed by Stoffel (2010). For the delimitation of the deposits, we made a 50meters buffer in the drainage, relating the location of the boulders with the drainages that could have transported and deposited the boulders. We also used the altimetry where the boulders are located and its proximity to slopes as criteria for the mapping.

2.2 PTVA Method

For the vulnerability, the PTVA (Papathoma Tsunami Vulnerability Assessment) method developed by Papathoma-Köhle (2016) was used. Then, two classes of criterion were selected: the constructive itself (building material, the presence of high walls, number of floors, the presence of large doors and windows) and the surrounding of the constructions (presence of vacant lots or wide-open area, the presence of blocks and their dimensions and proximity of buildings). Subsequently, the method of Multicriteria Evaluation (Voogd, 1983) was applied using a simple linear transformation to count each criterion and assign the weights. The weights were organized according to their importance for the application of the mitigation measures by the public power, as stated by Papathoma and Dominey - Howes (2003). This is the following assignment: Construction material (weight 7), High walls (weight 6), Presence of large / wide doors and windows (weight 5), Large land / wasteland (weight 4), Number of floors, Presence of blocks (weight 2) and Size of blocks (weight 1). In front of the counting and the assigning of weights, the vulnerability was calculated with the sum of the multiplication of each weight by the standardized count of each criterion. Thus, the final vulnerability was divided by the sum of the weights to be expressed in the scale of 0 to 1.

3. Results

3.1 Susceptibility / Morphometric Parameters

Considering the morphometric parameters and the morphology of debris flows deposits, all eight basins presented favorable conditions for debris flows (Table 1). There were high values of Drainage Density (Dd), mainly the Area 2 (A2) and the Guaxinduba basin of Area 1 (A1), where large blocks were also identified and the highest values of the Roughness Index (Ri), indicating its high sediment yield potential, along with the Palmital 1 and Gurutuba (A2) basins.

Table 1: Morphometric Parameters of the five basins in Area 1 and three basins in Area 2, with predominant lithology. Legend: Area (km²); Drainage Density (Dd) (km/km²); Ruggedness Index (Ri) (m/km); Circularity Index (Ci) (km²/km²); Relief Ratio (Rr); Drainage Hierarchy (Dh); Slope Mean Channel (Smc); Cc (Curvature Concave).
In highlight = Critical values.

Area	Basin	Area	*Dd*	*Ri*	*Ci*	*Rr*	*Dh*	*Smc*	*Cc*	Lithology (>50%)
1	Massaguaçu	20,5	1,7	1,6	0,55	132	3º	10º	-	Granitoids
	Guaxinduba	24,1	3,4	3,4	0,25	78	4º	10º	26%	Granitoids
	Aldeia	22.3	2.4	2,6	0,43	112	4º	11º	30%	Granitoids
	S. Antônio	40,0	2,2	2,0	0,43	94	5º	11º	20%	Granitoids Quartzites
	Pau d'alho	23,0	2,2	2,2	0,28	91	4º	14º	29%	Complex (gneiss-migmatite)
2	Palmital 1	0,8	7,7	3,8	0,61	299	3º	22º	25%	Phyllite, Metarenite
	Palmital 2	1,0	5,2	2,7	0,62	252	3º	23º	30%	Phyllite, Metarenite
	Gurutuba	0,5	5,1	8,7	0,42	170	2º	29º	27%	Phyllite, Metarenite /Granite

According to the Circularity Index (Ci), all basins have a more elongated shape (Ci <0.5), except Palmital 1 and Palmital 2, where the large and extra-large rock block deposits were identified, especially the Guaxinduba and Pau d'alho basins (Fig. 3B). According to literature, this elongated shape is more favorable to deflagration of debris flows in steep landscaping slopes (Crozier, 1986). However, two basins (Santo Antonio and Aldeia) presented a circular shape as well large deposits related to previous debris flows (Fig.3A). Although all basins show high values of Relief Ratio (Rr), indicating a significant potential of transport and flows, those with higher volumes of deposits had the lowest values of this index (Santo Antonio, Pau d'alho and Guaxinduba).

The Gurutuba basin (A2) has critical values in all morphometric parameters, where, in its lower portion, the large debris flows with large size deposits were mapped and the high destructive power (Fig. 3) and rapid flash floods that reached elevations between 1.90 and 2.60 m, destroying about 15 buildings.

The Palmital 1 and Palmital 2 basin, which also present critical values in all morphometric parameters, are tributaries of the Palmital river basin, wherein 2014, recorded mudflows and flash floods. All these basins drain into neighborhoods and districts of two cities (Itaóca and Apiaí) with urban and rural occupations, crops fields and forest.

In 2014 this area was affected by debris flows, mudflows and flash floods that destroyed more than 500 buildings, 300 people homeless and 25 people killed (Gramani and Arduin, 2015, Matos et al., 2016).

Fig. 3. Deposits in Santo Antônio basin (A), Pau d'alho basin (B), mudflows and flash floods in Itaóca city from 2014. Source: Itaoca municipality.

3.2 Vulnerability

Regarding the vulnerability 38 part of the basin were mapped (Fig. 4) with high (8%), average (70%) and low (22%) vulnerability and with a variation of 30% between the lowest vulnerability and the highest one. The high vulnerabilities (76% to 85%) are concentrated in the northern and central portions. Mean vulnerabilities (66% to 75%) are predominant and well distributed, with low vulnerabilities (55% to 65%) concentrated in the central and southern portions.

There was a variation of about 30% of the lowest vulnerability (55%) and the highest vulnerability (83%), as a result of the variation in the conditions of the vulnerability criteria. Some criteria were more important for the increase of the final vulnerability, like lack of high walls involving the constructions, presence of blocks in the surroundings and proximity of the constructions mapped with open lands. On the other hand, other criteria contributed to the reduction of vulnerability: masonry constructions, distance from vacant lots such as fields or vacant lots and absence of previous blocks of races.

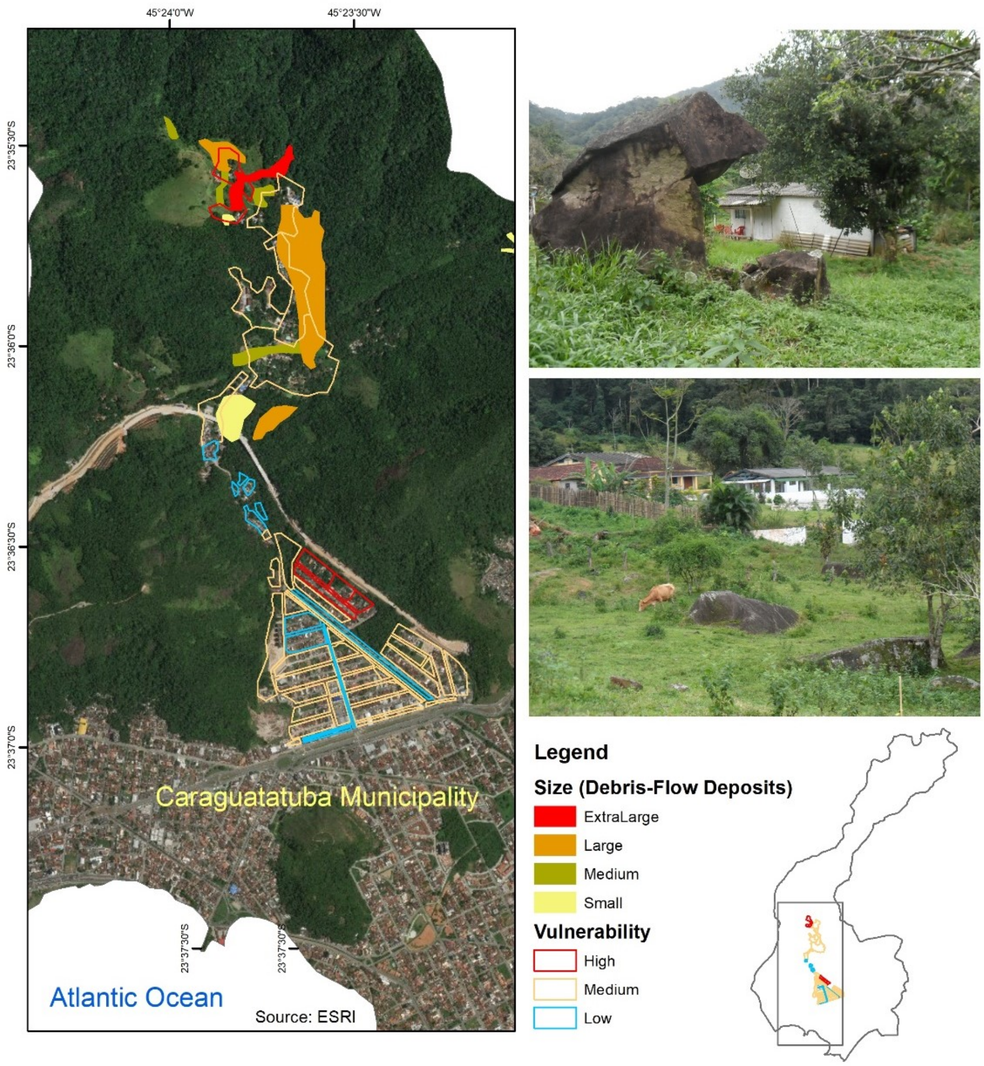

Fig. 4. Vulnerability map of buildings.

4. Conclusions

- No criterion was determinant in the final classification of the vulnerability and the result depends on the variation of a set of criteria that tends to increase or reduce the final vulnerability. In general, the condition of the constructions that most increased the vulnerability met the following criteria: 1) absence of high walls involving construction, 2) the presence of blocks in the surroundings, 3) proximity to buildings mapped with open land, and 4) buildings with only one floor
- There are still few studies on the spatialization, identification, and evaluation of the magnitude of debris flows in Brazil at basin scales. Thus, it is believed that these studies can contribute to future work that aims to identify the potential of watersheds in the generation of debris flows.
- It was not possible in this work to associate the susceptibility and the vulnerability for all analyzed basins. Future works will produce new maps of the deposits seeking to identify this association.

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